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# Stopping behavior in a VR driving simulator: A new clinical measure for the assessment of driving

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*Abstract*— **The driving privilege is a critical component of independent living for individuals who have acquired a brain injury. To date, measures of driving capacity following neurological compromise remain limited to gross performance measures, such as subjective behind the wheel evaluations. The current study demonstrates the use of a virtual reality (VR) driving simulator to provide objective and precise measures of driving behavior not previously available for clinical assessment. Driving performance related to Stop Sign (SS) intersections are compared between adults with and without acquired brain injury. The findings indicate that new driving performance measures can be calculated with VR driving simulations, and that these measures may have further implications for examining driving capacity following neurological compromise.**

## I. Introduction

The ability to drive an automobile promotes a sense of self sufficiency and freedom. There is little doubt that automobiles are vital factors in millions of American's lives and driving serves as a crucial mode of transportation for many individuals socially, financially, and individually. Driving also results in thousands of yearly fatalities. For example, one study done by the U.S. Department of transportation found that many fatalities occurred at traffic signals and stop signs [1]. In 1999 and 2000, they reported 9,951 fatal crashes at various traffic signals. Stop signs markedly involve more fatal crashes, yielding a total of 13,627 fatal crashes in 1999 and 2000. Of these fatal crashes, 21% resulted from a failure to obey the signal, whereas 23% resulted from a failure to yield the right of way. Some significant causes of crashes included inattention, speeding, and obscured vision. The study concluded that the probability of a fatal crash at a stop sign is roughly 2.5 times higher than at traffic signals.

Such knowledge of where, how, and why crashes occur is crucial to guide changes in traffic laws for increased safety. However, research on driving accidents has typically focused on healthy individuals with full cognitive capacity. By contrast, there is a dearth of research examining these same parameters among drivers with acquired brain injuries (ABI), where driving skills can be impeded by cognitive impairments. In fact, there are no studies that have directly examined specific driving errors (e.g. stop sign behavior) or violations of drivers with ABI. Yet, identifying high risk driving scenarios can be helpful in guiding driver assessment and retraining for those individuals who seek to regain their driving privileges following ABI.

For individuals with ABI, the loss of driving privileges impacts them emotionally [2,3], interpersonally [4], and financially [5]. Yet, the ability to drive is a complex behavior involving myriad cognitive, sensory, and behavioral components. Because driving requires the integration of these multiple components, it is often an ability that becomes difficult for individuals with ABI. Furthermore, the current clinical tools that are used to determine driving capacity after neurological compromise have been flawed by subjective observations, lack of ecologically-validity and lack of standardization [6].

Virtual Reality (VR) driving simulators can serve as a useful tool in addressing these limitations and assessing the various demands of driving. VR driving simulators allow the use of realistic driving scenarios and can provide multiple objective measures of driving performance simultaneously. Research conducted with VR driving simulators with adults with traumatic brain injury have demonstrated that VR driving measures can discriminate between drivers with and without brain injury [7, 8] and that some measures from VR driving are correlated with cognitive domains relevant to driving capacity (i.e., attention) [9].

The performance measures examined within these studies have included variables such as vehicle speed, lane use, response to traffic signals, and other basic driving

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performance. However, the use of VR driving simulators offers the opportunity to measure more specific behaviors of driving, such as driving behaviors for managing a stop sign intersection. Given the high risk associated with stop sign management among normal drivers, the current study sought to use a VR driving simulator to begin to examine specific measures of driving performance related to stop sign intersections among drivers with acquired brain injury.

## II. PROCEDURE

### A. Participants

The sample included a total of 24 adult participants, 15 individuals with acquired brain injury (ABI) and 9 healthy controls (HC) matched on age and driving experience. Of the ABI participants, 67% (n=10) experienced a moderate to severe traumatic brain injury (TBI), while the other 33% (n=5) experienced a cerebrovascular accident (CVA) or stroke. Medical records obtained from rehabilitation hospitals and/or treating physicians confirmed diagnosis of injury for ABI participants. Characteristics of the sample are provided in Table 1.

TABLE 1
CHARACTERISTICS OF THE SAMPLE

| | | ABI (n=15) | HC (n=9) |
|---|---|---|---|
| Age (yrs) | | 38.8 | 36.2 |
| Gender | *female* | 40% | 44% |
| | *male* | 60% | 56% |
| Driving Experience (yrs) | | 19.6 | 19.0 |

Participants with prior history of severe psychiatric disturbances, extreme motion sickness, substance abuse or history of prior TBI/CVA or any major medical/ neurological condition were excluded from the study. Individuals who required the use of assistive driving devices were not included in the study. At the time of testing all participants held a valid driver's license in the states of New Jersey, New York or Connecticut. Reports from the Department of Motor Vehicles were obtained for verification of driving status for all participants. Individuals with a history of loss of driving privileges or reckless driving were not included in the study. All participants were required to have a minimum of one year of continuous driving experience, with ABI participants meeting this requirement prior to injury. Participants were also required to meet the minimum visual requirement for their licensing state.

### B. The VR Driving Simulator (VRDS)

The VRDS is composed of hardware and software elements. The hardware includes a steering wheel and gas/brake foot pedals (Microsoft Sidewinder), and a head mounted display Proview™ XL50 Virtual Reality Display headset with 1024x768 resolution and 50° diagonal, 30° (V) x 40° (H) field of view, (Kaiser Electro-Optics, Inc.) with a motion track with 2 ms latency and 1° accuracy (Intersense I-Cube gyroscopic / geomagnetic sensor). The virtual environments were delivered using a desktop computer and display (Gateway multiprocessor 701 MHz Pentiums). The video update rate is 60 Hz (60 frames per second). In addition to the visual feedback, the VR-DR provides auditory (e.g. sound of car engine) and tactile feedback (e.g. force feedback from the steering wheel) to increase the VR experience for the user

The VRDS software was custom designed for this application and includes a virtual driving route that represents several typical driving scenarios that individuals could encounter while performing daily activities (e.g., pedestrian crossing road, traffic). It was patterned after the actual driving route used for clinical driver evaluations conducted by the Kessler Institutes for Rehabilitation in West Orange, New Jersey. Total time to complete the VR driving simulator course was approximately 25- 35 minutes. The entire VRDS driving course has nine separate areas (e.g., residential, merging, commercial) each with unique driving scenarios and demands. For the current study, one specific area of the route was selected because it included multiple stop sign intersections. The area was approximately 4,075 feet in length. Specifically, the virtual route analyzed required the individual to navigate one 4-way-stop intersection [stop sign 1 (SS1)] and two regular (2-way) stop sign intersections [stop signs 2 (SS2) and 3 (SS3)].

The VRDS automatically generates four quantitative output variables that are sampled every 200 milliseconds during simulation. No filtering is performed. These measures include speed (in miles per hour), deviation from the center of the lane (in feet), distance to a challenge (e.g., stop sign) (in feet) and head turn angle to the left or right (in degrees). These primary measures were used to calculate four new measures of driving performance related to managing a stop sign (SS) intersection were defined (as defined below).

### C. Procedures

At the initiation of the testing session, all participants completed an Institutional Review Board consent form and required HIPAA authorization forms. Prior to administration of the VRDS, all participants were provided with an opportunity to practice driving in the VRDS. After practice trial, participants were administered the complete VRDS route, a cognitive battery and the Kennedy Simulation Sickness Questionnaire. For the current study, only individuals who did not experience simulation sickness were included.

### D. Defining VRDS Driving Performance Measures

Prior to examining individual performance, definition of the area of interest or stop sign zone was determined. Specifically, a stop sign zone is defined as the area both 25 feet before and after each stop sign. The measure of 25 ft. was determined based on published guidelines of the Department of Motor Vehicles in the States of NJ and NY. Before this criterion was applied, initial evaluation of the data revealed that a small number of the participants did not stop at all for some signs. Specifically, a total of six incidents where the driver did not come to a stop (defined as speed = 0 mph) were identified across all three stop sign intersections of the virtual driving environment. Further evaluation revealed that of the six incidents, 83% (5) were initiated by a participant with ABI and only 17% (1) were initiated by a healthy control. These participants were subsequently excluded from the final analysis.

For the remaining participants who did stop for each sign, we evaluated stopping patterns at the three consecutive stop sign intersections. The driving performance variables included:

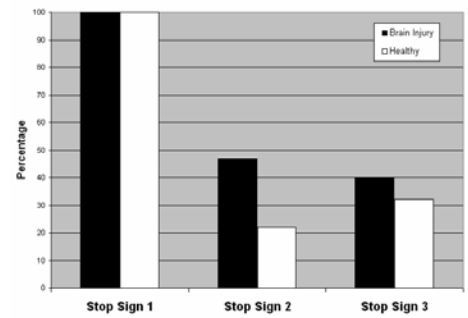
- *"Full stop"* was defined as a vehicle speed of 0 mph
- *"Distance"* from the stop sign was calculated in feet
- *"Time"* at stop sign was defined as the total time in milliseconds the individuals was at a "full stop"
- *"Approaching speed"* was calculated as the average speed during the 25 feet before the individual came to a full stop.
- *"Departing speed"* was calculated as the average speed during the 25 feet after the stop sign.

## III. Results

### A. Full Stop versus No-Stop

Evaluation of driving performance across the three stop signs revealed that frequency of "no stops" within the stop zone decreased as individuals progressed through the multiple stop sign intersections (see Figure 1). Specifically, none of the participants executed a "full stop" within the designated stop sign zone at the first intersection. At interactions SS2 and SS3, the majority of participants in both groups successfully executed the "full stop". However, a small percentage continued to not stop. Specifically, at SS2 only 22% of the HC group did not come to a "full stop" while 47% of the ABI group did not stop. At the SS3, 32% of the HC group did not stop, while 40% of the ABI group did not stop. It should be noted that individuals that did not execute a "full stop" did show evidence of either stopping outside the stop sign zone (greater than 25 feet away) or slowing down as they approached the stop sign, indicating a more "rolling stop" behavior.

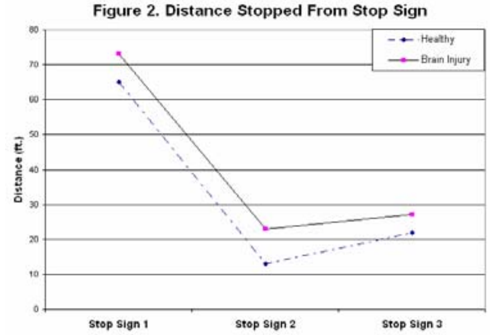
Figure 1. Percentage of "No Stops"




### B. Distance from Stop Sign

Evaluation of how far individual stopped at the stop sign also revealed a pattern of improved performance as participants drove from the first (SS1) to the last (SS3) stop sign intersection. Specifically, at SS1 both drivers with and without ABI came to a "full stop" over 50 feet (ABI= 73 ft., SD=14.7, HC=65 ft., SD=6.43) before the stop sign (two times greater than the established SS zone). This improved remarkably at SS2, with ABI averaging a stopping distance of 23 ft.(SD=16) and the HC group averaging 13 ft.(SD=14) At SS3, the difference between the groups decreased with the ABI group averaging 27 ft.(SD=16.4) and the HC group averaging 22 ft.(SD=6.2) (Fig.2).

Figure 2. Distance Stopped From Stop Sign




### C. Time at Stop Sign

Evaluation of how long individuals spent at each stop sign intersection was examined. The data also indicated some changes in behavior as drivers moved from the first (SS1) to the last stop sign (SS3). Specifically, at SS1, the ABI group remained at the stop sign an average of 3.7 seconds, while the HC group averaged 5.0 seconds. At SS2, the ABI group averaged 4.3 seconds while the HC group remained at 5.0 seconds. By SS3 both groups shorted their stop duration (ABI=2.7 sec.; HC=3.8 sec). Of note was the fact that in all three SS intersections, the ABI group remained at the SS intersection for a shorter period of time.

### D. Approaching and Departing Speed

Differences in approaching and departing speeds around the SS intersection were examined between the two groups.

TABLE 2
SPEED MANAGEMENT AROUND STOP SIGN

| | Stop Sign 1 | Stop Sign 2 | Stop Sign 3 |
|---|---|---|---|
| Approaching (mph) | | | |
| *Brain Injury* | 7 (SD=2.3) | 7 (SD=4) | 7 (SD=2.6) |
| *Healthy Control* | 6 (SD=1.9) | 7 (SD=2.2) | 7 (SD=2.1) |
| Departing (mph) | | | |
| *Brain Injury* | 24(SD=3.6) | 16 (SD=3.8) | 17(SD=5.6) |
| *Healthy Control* | 25 (SD= 2) | 13 (SD=5.3) | 17 (SD=5.5) |

Expectedly low approaching speeds were observed in both groups across all three SS intersections (see Table 2). In contrast, departing speeds were higher, although SS2 generated lower departing speeds than the other intersections for both groups.

## IV. DISCUSSION

The ability to drive an automobile is for many an important aspect of everyday functioning. Unfortunately, our clinical tools for evaluating fitness for returning to driving following ABI remain limited.

The use of a VRDS can offer clinicians numerous advantages that are not available through traditional methodologies, including objective measures of driving performance and safe but challenging exposure to driving challenges. The current project exemplifies this through the identification of specific and objective VRDS measures that quantify driving performance related to managing a stop sign intersection. While such specific measures have been examined in normal drivers, the study represents the first description of this VRDS driving behavior in a clinical population.

For both groups, the findings serve to demonstrate a pattern of improved performance with repeated exposure. Specifically, this was seen in two variables: the decreased frequency of "no stops" and the distance participants stopped from the stop sign as they progressed through the environment. As expected both groups demonstrated atypical performance at initiation (Stop Sign 1). This was due to unfamiliarity with the VRDS and the virtual environment and a lack of depth and perceptual accommodation. Interestingly, while both groups showed learning patterns across the three stop sign intersections, the observed patterns were different between the two groups. These findings raise questions regarding learning in the virtual environment and may represent a level of accommodation that occurs as individuals become more accustomed to navigating/driving in the virtual environments. It also shows promise that VRDS can possibly serve as a rehabilitation tool, as individuals show learning and marked improvement even in this short period of time.

While between-group differences were not anticipated, the findings indicate some differences in performance with disability (with the ABI group showing greater difficulties). This is despite the fact that both groups were matched on driving experience, and that the ABI group included only drivers who had regained driving privileges. This raises numerous questions regarding potential issues of usability of VRDS with clinical populations [10] and the need for defining the cognitive demand of VRDS driving performance.

While the current study is limited by a small sample size, these findings underscore the need for further investigation into defining VRDS measures and their relationship to actual driving behavior. These VRDS stopping performance measures are consistent with transportation literature. They represent more precise measurement then what is currently clinically available. As such they may offer new insight into defining driving capacity among clinical populations. This is one of the promises made by VR driving simulation. However, a significant amount of work still remains to define the clinical validity of VRDS driving performance measures such as those proposed here.

## ACKNOWLEDGMENT

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